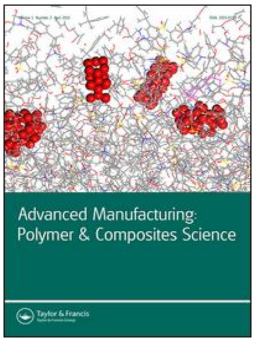

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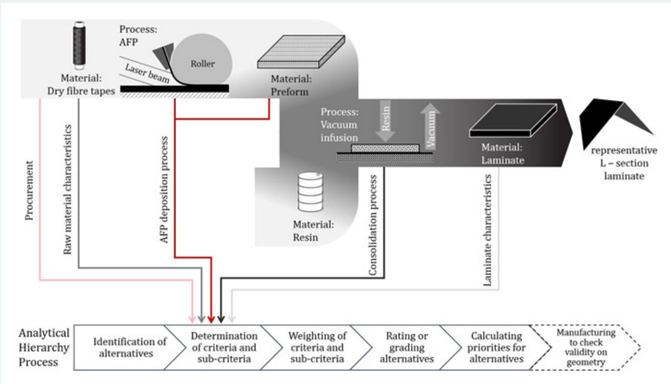
Laura Veldenz[a], Mattia Di Francesco[a], Peter Giddings[a], Byung Chul Kim[b] and Kevin Potter[b]

[a]The National Composites Centre, Bristol, UK; [b]Advanced Composites Centre for Innovation and Science, Department of Aerospace Engineering, University of Bristol, Bristol, UK

ABSTRACT

Dry fiber tapes have become an alternative to pre-impregnated tapes for automated fiber placement. However, their industrial adoption is inhibited by high upfront research and development cost. To reduce the cost of material selection as part of such an investment, this work presents the application of the analytical hierarchy process (AHP) to material selection with a focus on material processability and manufacturing quality. The selection is based on procurement, material and its performance throughout the manufacturing process, and some laminate quality indicators. Criteria and sub-criteria were identified and implemented into the AHP. This established decision making tool was compared to a more efficient derivative using the chain of interaction method. Two materials, including the selected material, were used to manufacture a small-scale L-section composite component. This demonstrates that the proposed material selection method predicted the more preferable material for manufacturing quality when applied to a complex geometry.



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Introduction

The demand for carbon fiber reinforced composites is estimated to grow significantly over the next decade, especially for use in the aerospace industry [1,2]. This growth has led to research and development focused on automated manufacturing processes to lower cost and increase productivity. Automated fiber placement (AFP) using pre-impregnated materials (prepreg) is already widely used in the aerospace industry on flying parts [3]. Only more recently, dry fiber tapes suitable for automated deposition by conventional AFP machines were developed as a low cost and out-of-autoclave solution, where the resin is introduced at a later stage, after the material deposition process. This technology is in its early stages of development and material suppliers are entering the market with a range of different fiber materials. Due to the novelty of the process, very limited research has been conducted and published, which makes it challenging to select the most suitable material for a specific application. Furthermore, particularly in the AFP process, material and manufacturing equipment is strongly linked and cannot be assessed separately. Material driven manufacturing issues can increase the production cost (e.g. due to machine stoppage) and can have a significant effect on the properties of the laminate (e.g. due to defects). Therefore, the early stage of product development requires a significant budget and time commitment. A reliable method for material suitability assessment is essential to minimise iterative

CONTACT Laura Veldenz laura.veldenz@nccuk.com The National Composites Centre, Bristol and Bath Science Park, Bristol BS16 7FS, UK.

Table 1. Different material trade names and provided information.

Material ID	Supplier	Product name	Nominal fiber density, g/cm^3	Nominal areal weight, g/m^2	Nominal tape width, mm	Binder type	Binder application	Tape type
A	Cytec Solvay Group, US	TX1100 IMS65 [38]	1.78	196	6.35	EP	CF veil + EP powder	Slit tape
B	Toho Tenax Europe GmbH, Japan	TENAX-E HTS40 X030	1.76	126	6.35	EP	EP powder	Tow based
C	Porcher Industries, France	TP bindered yarn	1.77	126	6.35	TP	TP powder	Tow based
D	Hexcel Corporation, US	HiTape® [33]	1.79	210	6.35	TP	TP veil	Tow based
E	Porcher Industries, France	TP bindered yarn	1.78	261	6.35	TP	EP powder	Tow based

CF = carbon fiber; EP = epoxy based; TP = thermoplastic based.

manufacturing trials, which are currently commonplace in industrial development.

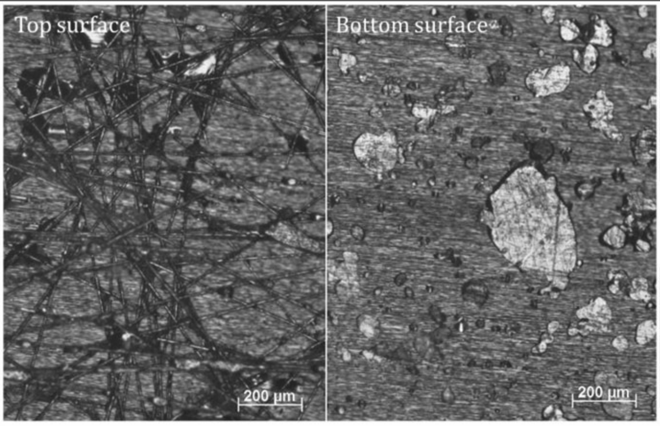
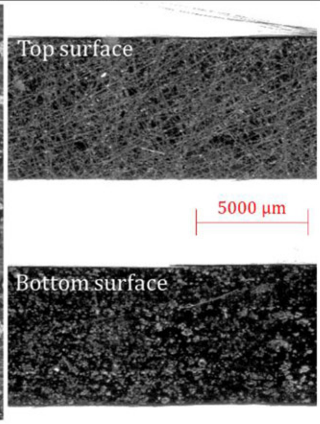
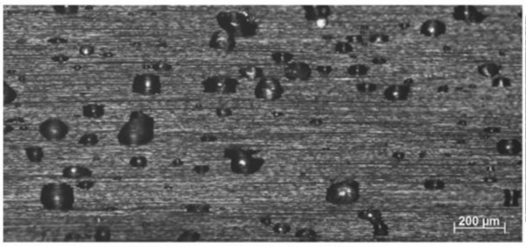
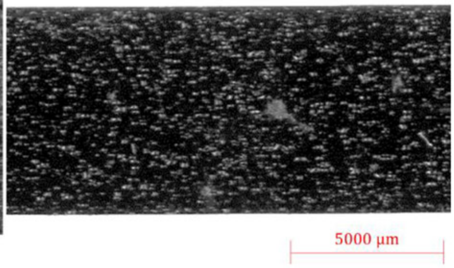
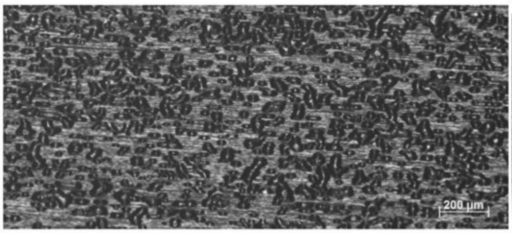
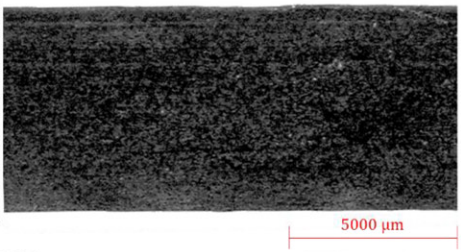
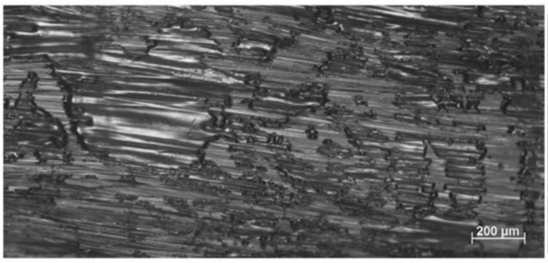
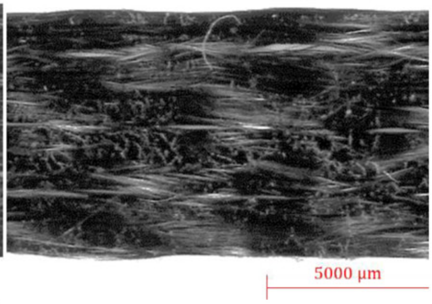
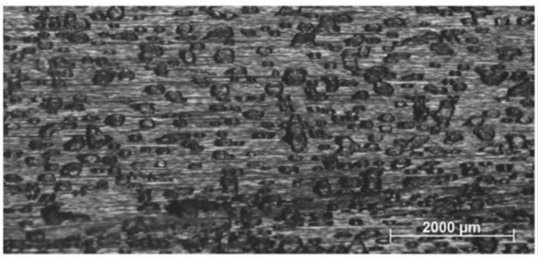
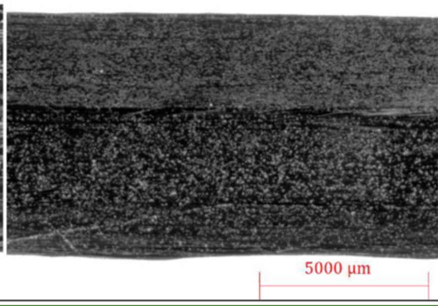
Multi-criteria decision-making tools are suitable for such material selection to enable objective, structured, transparent and cost effective decision making [4]. It is advised to use such tools as guidance only in an engineering context, as the choice of a decision making tool (decision making paradox) and the considered criteria may have an impact on the result [5]. However, the benefits outweigh the drawbacks: in addition to guiding material selection, the assessment process can build up a reusable database when the same materials are the candidates to be used for different applications.

The material selection methods most frequently used feature the same three basic steps: (1) criteria and alternatives are established; (2) numerical measures are determined to the relative importance of the criteria and alternatives are assessed and (3) an overall ranking is calculated [6]. One of the main differences among decision-making tools is whether the weightings for the criteria can be determined as part of the process or not. Commonly used examples such as 'Technique for Order of Preference by Similarity to Ideal Solution' (TOPSIS), 'ELimination Et Choix Traduisant la REalité (ELimination and Choice Expressing REality)' (ELECTRE) and 'Simple Additive Weighting Method' (SAW) require weighting factors as an input, but do not offer a method to determine the weighting, or are unable to handle objective and subjective criteria at the same time [7–9].

In the case of a less mature and therefore only partially characterized manufacturing process, the weighting factors of different criteria cannot easily be predefined. Therefore, a systematic approach to defining the weighting factors is needed. A method that offers a way to define criteria weight as part of the process is the analytical hierarchy process (AHP) and derivatives thereof [10,11]. The AHP allows the use of qualitative and quantitative criteria in the same model and has been applied in a wide range of context, but only limited examples on composite materials and manufacture thereof are available. While the AHP is the most suitable selection method in this instance, it was shown by Adhikari and Mirshams that it is beneficial to interrogate materials using multiple selection tools to gain confidence in the result [12]. Therefore, as a second method a variation of the AHP will be used for comparison. This less frequently used selection method in the area of material selection is the AHP extension chain of interactions (CoI), as a way of weighting criteria [13]. While the weighting of each criterion is reliant on experts' judgements in the AHP, the CoI method uses the number of interactions between criteria to calculate the weighting of a criterion instead. The AHP extended by CoI (AHP + CoI) could minimise the subjective influence of the decision makers, which has proven to be successful and less costly in the context of supplier selection [13].

The AHP process has been successfully applied to identify a design concept of a composite bumper beam [14], to select a fiber material for an automotive brake lever [15], to select a matrix for an automotive armrest [16] and to determine the most suitable composites manufacturing method for a bicycle crank arm [17]. In the case of the material selection for the automotive brake lever, only the four criteria weight (density), cost (raw material cost) and performance (strength and stiffness) were considered, the manufacturing process of the composite material was excluded. Often, a sensitivity analysis verified the robustness of the decision against various scenarios. The process selection by Luqman et al. took into account a wider range of criteria, such as production characteristic, the design, cost, material and ease of maintenance [17]. While these works indicate that the use of AHP was suitable for composite materials, parts have not been manufactured to verify the selection made through AHP.

Table 2. Micrographs (left) and high-resolution scans (right) of Material A (top) to E (bottom).

	Micrograph	High-resolution scan
A		
B		
C		
D		
E		

In related areas, such as additive manufacturing, material selection processes are also frequently used. Zaman et al. use a very detailed list of criteria for both, material and machine, however the performance of a material on a particular machine is not considered [18]. In this and similar work, the material selection often relies on Ashby charts or other material property data as input to the process [12,18–20], assuming that the material performance is independent of the machine and manufacturing process. While this may be the case for manufacturing processes using isotropic, single-phased materials, this assumption does not apply to composite material manufacture. The influence of manufacturing defects

Figure 1. Left: convex corner defects (wrinkles), right: concave corner defects (bridging), adapted from [37].

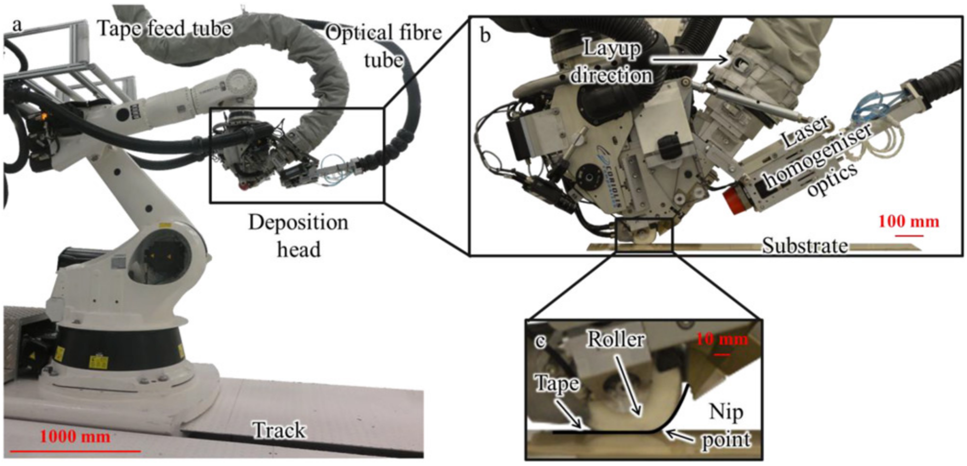


Figure 2. (a) AFP machine (National Composites Centre, UK), (b) details of the deposition head and (c) roller and nip-point of the deposition head.

on a wide range of material properties is widely recognized [21–24], and more recently more specific research regarding defects induced by the AFP and subsequent consolidation process [25–29] and therefore the performance of the material during the manufacturing process has to be included.

This paper aims to:

1. Identify sophisticated material selection criteria for AHP based on industrial scale AFP manufacturing trials and in-depth knowledge of different dry tape materials.
2. Apply the AHP to select a dry fiber AFP material based on small-scale manufacturing trials and build up a database with material and machine specific test results.
3. Compare two different weighting methods used in AHP (weightings established through experts' judgement compared to using CoI) to address the the dependence of the approach on the criteria weighting.
4. Identify the most suitable material for the presented case out of the available options based on qualitative and quantitative metrics, and verify the selection method through manufacturing trials of an industrially representative demonstrator.

Materials and methods

Dry fiber tapes

The dry tape materials assessed in this work were limited to commercially available products for AFP. There is currently no dominant design on the market, and therefore different suppliers provide substantially different products. The specific composition and manufacturing processes of the different materials is proprietary information of the suppliers, but some basic information on structure and constituents has been provided and is shown in Table 1.

The variation in the constituents and manufacturing process of the dry fiber materials results in significant differences in their processability on an AFP machine. The differences originate in their dissimilar manufacturing methods. To shape the raw material into tapes, either a binder stabilized broad good is produced and slit into tapes (as Material A), referred to as slit tapes; or a raw carbon tow (or roving) is transformed into a tape form, and then stabilized with a binder.

A further difference in dry fiber materials is caused by different binder application techniques. The binder used in the different tapes is either epoxy or thermoplastic based and was applied using different methods, which is part of the proprietary information from the suppliers. In Table 2, the different resulting surfaces of the chosen materials are shown, exhibiting different surface characteristics due to different binder application methods. Most materials have the same finish on both sides, except Material A that has distinct features on either side of the tape. Material A has a carbon fiber veil on the top side and epoxy-based binder spots on the bottom side. Materials B, C and E have binder spots evenly distributed on both sides, where B exhibits a lower density of spots than C and E. Material D has a thermoplastic fiber veil on both sides.

Table 3. Criteria and sub-criteria used in the AHP.

Criteria	Sub-criteria	Assessment	Impact
Procurement	Lead time, weeks	Obtained by counting the weeks between order and arrival on site.	Can be a critical factor for completing a project on time and budget.
	Risk	Likelihood of receiving false information from the supplier (e.g. wrong lead time, wrong technical information) and the risk of a supplier terminating production.	
	Customer service	Answering questions about procurement satisfactorily (e.g. prompt response to inquiries and its validity, etc.).	
	Technical support	Answering questions about manufacturing satisfactorily (e.g. recommendation of processing parameters).	
	Material cost, £/kg	Obtained through quotes from the suppliers.	Can be prohibitive to the usage of a material.
	Procurement conditions	Restrictions on material usage (e.g. use of specific resins or any other formal constraints).	Relevant for the R&D environment in which a project was completed.
Raw material characteristics	Width deviation, mm	Double standard deviation of the tape width, indicating its consistency.	Random width deviation may cause unintended gaps and overlaps in the preform [39,40].
	Width compliance, mm	Width deviation from nominal width (in this case 6.35 mm), indicating compliance to product specification [31,41].	Material consistently too wide or too narrow for the machine may cause distortion of the tapes or gaps.
	Material complexity	Number of constituents within the material (reflecting the material and production costs)	Taken as a proxy of the potential for raw material cost to decrease in the future.
	Binder quantity deviation, wt.%	No binder quantity target is available, only the consistency of the binder application is used (double standard deviation of binder quantity) [31].	May cause local inconsistencies in the preform quality and impact the infusion behavior.
AFP deposition process	Defect occurrence, count/100 m	The number of defects per 100 meters counted by visual inspection without accounting for severity.	Defects have a negative effect on ultimate strength of the laminate (up to 13% difference to material without defects) [29].
	Preform fiber volume fraction (preform V_f), %	Calculated using nominal fiber density, nominal areal weight, number of plies and measured preform thickness.	A high preform V_f is a positive indicator for high V_f in the part. A preform V_f should be between 50 and 55% [31].
	Areal weight, g/m^2	Measured by weighing a known length of material on a scale [31].	A high fiber areal weight is a positive indicator for high deposition rate.
	Steering capability	Visual assessment of the equality of the steered tapes by trained technician.	Indicates the suitability of the material for deposition of complex structures [42].
	Preform integrity	Preform integrity is the perceived stiffness and coherence assessed by the technician handling the preform.	A stiff preform is a positive indicator for ease of handling.
Consolidation process	Infusion time, min	Measured between opening the resin valve and the completion of infusion when resin appears at the outlet.	A faster fill of the preform indicates a higher production rate.
	Bulk factor (BF) of preform	Ratio of the measured preform thickness to the measured thickness of the consolidated laminate.	A low bulk factor is a positive indicator to avoid wrinkles when closing the tool in complex geometries [37,43,44], common values are 1.1 to 1.5 for prepreg materials [45].
Laminate characteristics	Void content, %	Percentage of air trapped in the laminate measured using microscopy. (Three cut samples, ten images per cross section.)	A low void content is a positive indicator for a high-quality laminate [46–48].
	Laminate fiber volume fraction (laminate V_f), %	Calculated based on nominal fiber density, nominal areal weight, number of plies and measured total laminate thickness.	A high V_f is a positive indicator for a high-quality laminate [49]. The target value is 55%.
	Geometrical tolerance, mm	Deviation of the thickness against the nominal tool cavity of 3 mm.	Predictability of the outcome of the process is considered positive.
	Ply areal weight, g/m^2	Measured by weighing a known length of material on a scale [31].	Thinner plies are considered positive for high mechanical performance of the laminate [50].

Notes: If no unit is given, the criterion is assessed qualitatively by pairwise comparison; uniformity is considered a positive feature.

Automated dry fiber placement

In order to assess the characteristics of different dry tape materials and their processability on an AFP machine, a series of lay-up tests were carried out. These tests investigated the quantitative and some qualitative sub-criteria required as input to the AHP. The process parameters were established within a day of trial and error and visual assessment, where possible in collaboration with the respective material supplier. The deposition velocity, compaction pressure and machine hardware was kept constant. The use of a single deposition speed eliminates the need to establish a function to control laser power and deposition speed, only one laser power has to be established [30]. The

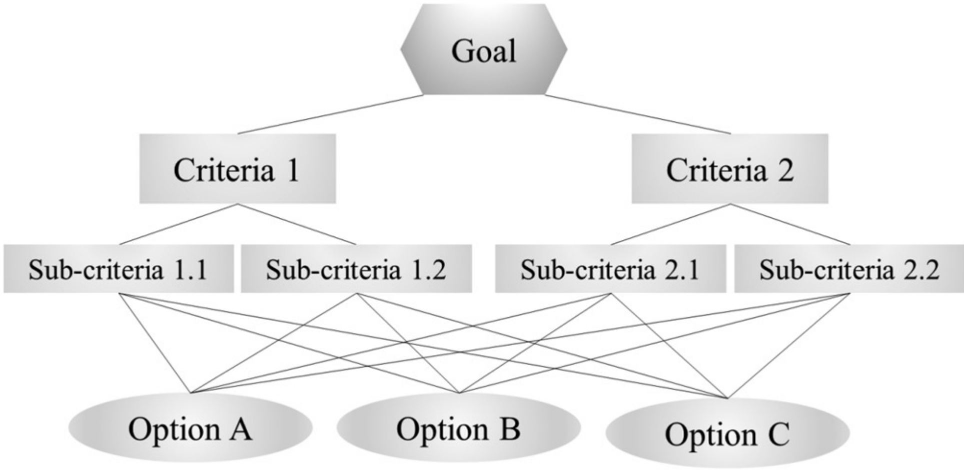


Figure 3. Simplified structure of the hierarchy used in the AHP, adapted from [13].

chosen temperature for deposition delivered a preform fiber volume fraction within 95% of the maximum achievable fiber volume fraction achievable on the used system. While this is a quick way of determining the processing parameters, the drawback to this approach is that the ideal conditions may not have been used for deposition. A high preform fiber volume fraction was considered favorable over lower values to mitigate potential defect generation during consolidation similar to prepreg material processing (see Figure 1).

The AFP system used for this work is equipped with a laser-heater supplied by Coriolis Composites SAS (Queven, France), see Figure 2. The machine deposits eight 6.35 mm wide tapes. The bobbins of dry fiber material are mounted in an environment-controlled creel and guided through individual channels to the deposition head. When the material leaves the deposition head, it is heated by a 3 kW diode laser with a wavelength of 1025 ± 10 nm and a laser beam size at the focal point of 8 mm × 57 mm to activate the binder. The processing temperature was measured as close to the nip-point as possible, where the incoming material meets the substrate (see Figure 2(c)). The materials are deposited at a constant speed of 400 mm/s. The flexible roller (40 Shore hardness, 60 mm wide, Ø = 70 mm) applies a compaction force of 446 ± 23 N (95% confidence interval), to promote adhesion of the incoming tapes to the substrate.

The as-supplied material was tested after it passed the tape feeding system of the machine to capture possible distortions caused by the feeding process (e.g. contact with rollers and guiding elements). A flat preform with a stacking sequence of $[0/90]_{ns}$ was manufactured with each material using the same machine program defining the fiber paths and identical processing parameters apart from deposition temperature, as discussed. The number of plies was flexibly chosen to fill the 3 mm deep cavity of the mold, which led to a fiber volume fraction as close to 55% as possible. These preforms were infused with an epoxy resin in a closed mold (500 mm × 500 mm × 3 mm). The epoxy resin used was Epikote RM135/H137 (Hexcel, US) and the preform was infused peripherally under vacuum pressure only keeping the tool temperature at 30 °C with the resin outlet in the center [31].

Analytical hierarchy process

The first step in the AHP is the determination of criteria. In addition to the authors, staff of the National Composites Centre considered experts in fields closely related to dry fiber AFP were consulted to list relevant criteria and sub-criteria. The identified criteria were procurement, manufacturing processes and the assessment of the resulting laminate. The sub-criteria break down each criterion into assessable components, and their definitions are shown in Table 3.

All materials were assessed with the methods outlined in Table 3, but not all materials were assessed through to the end of the process. Materials were excluded from further experimental work, if

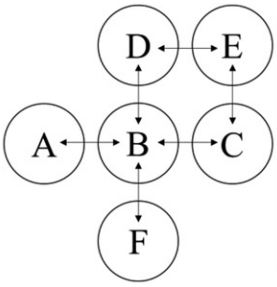
- The preform manufacturing has >200 defects per 100 m and/or
- The preform was not fully infused whereby the flow front is stagnant for 20 min.

The second step is to determine the relative importance of different criteria as a set of normalized weights, W_i. The same principle was applied to the sub-criteria yielding the weights $w_{i,j}$. The scores for all the sub-criteria $s_{i,j}$ were determined and then combined using

$$S = \sum_{i,j} W_i w_{i,j} s_{i,j} \tag{1}$$

where S is the overall and comparable score. The concept of the hierarchy is shown in Figure 3.

Two different approaches to determine the relative importance of the criteria weights were used in



	A	B	C	D	E	F
A	-	1	0	0	0	0
B	1	-	1	1	0	1
C	0	1	-	1	1	0
D	0	1	0	-	1	0
E	0	0	1	1	-	0
F	0	1	0	0	0	-
Total	1	4	2	2	2	1

	Factors
A	1/12 = 0.08
B	4/12 = 0.3
C	2/12 = 0.17
D	2/12 = 0.17
E	2/12 = 0.17
F	1/12 = 0.08
Total	12/12 = 1

Figure 4. Exemplary process of CoI. Left: diagrammatic representation of CoI; center: CoI responses for the given example; right: resulting elative weightings of criteria (factors), adapted from [13].

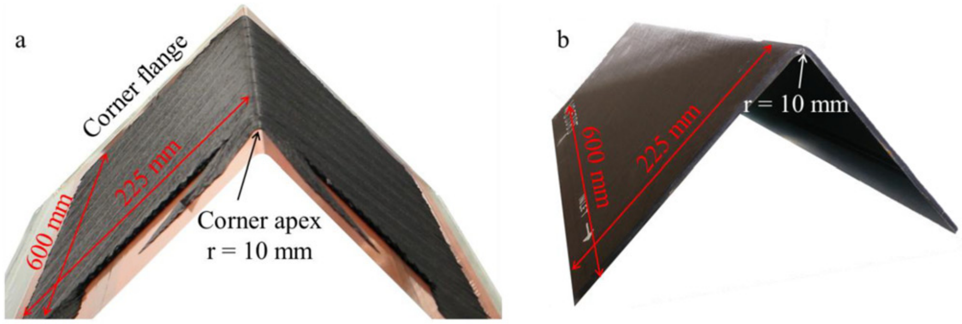


Figure 5. (a) Dimensions of corner preform used to support the material choice including detail of the corner apex; (b) infused laminate.

Table 4. Results of all quantitative material test results.

		Results				
Sub-criteria name	Unit	A	B	C	D	E
Lead time	weeks	52	**3**	**3**	**3**	**3**
Material cost	£/kg	223	**80**	**80**	114	100
Double standard deviation of width	mm	**0.2**	0.8	0.6	0.4	0.4
Deviation from nominal width	mm	0.2	0.4	**0.0**	0.5	0.3
Material complexity	n/a	8	**4**	**4**	5	**4**
Double standard deviation of binder quantity	wt.%	**0.79**	1.73	2.05	1.15	2.0[a]
Defect occurrence	count/100 m	24	195	244	84	**19**
Preform V_f	%	54.2%	**55.8%**	–[c]	43.9%	33.8%
Measured ply areal weight	g/m^2	211	128	139	203	268
Infusion time	h	**1**	–[b]	–[c]	2.5	2
Bulk factor		**1.0**	**1.0**	–[c]	1.2	1.6
Void content	%	1.7	–[b]	–[c]	**0.5**	0.8
Laminate V_f	%	**50.2**	–[b]	–[c]	43.8	47.5
Ply areal weight	g/m^2	211	–[b]	–[c]	**203**	268
Geometrical tolerance	mm	**0.0**	**0.0**	–[c]	0.2	0.1

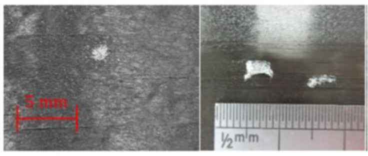
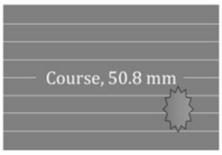
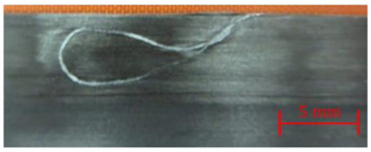
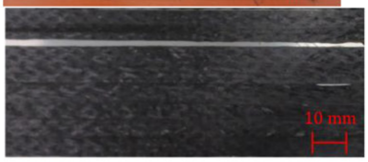
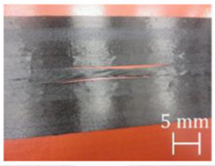
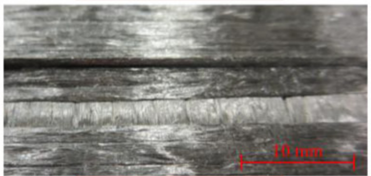
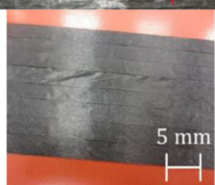
Bold: best value achieved.
[a]Data provided by supplier.
[b]Did not fully infuse.
[c]Fault count higher than permitted.

this work. In the first approach, the established AHP, the criteria weights W_i and $w_{i,j}$ are determined by pairwise comparison. Two criteria are compared at a time using a scale of 1–9, followed by a consistency check [10,11].[1] Weightings are derived from experience and potentially incomplete knowledge. In this case, all experts have gathered their knowledge and experience in related fields as the dry fiber AFP technology is still immature. If the consistency check fails, it indicates that the experts are unable to agree and all options are given equal weighting. The experts were asked to base their decisions on a specific application; a small-scale, thin L-shaped section.

A second approach to determine the weighting of the criteria is CoI, which was initially developed to cut the cost of gathering the experts' judgement. CoI reduces the reliance on subjective estimates and perceptions [13]. This method gives a higher weight to a criterion dependent on the number of other criteria with which it interacts (i.e. has a direct

[1]'The procedure requires calculating the "inconsistency index," that is, the difference between the largest eigenvalue and the number of elements of the matrix, divided by the number of elements minus one. The largest eigenvalue of a matrix of perfectly consistent comparisons equals the number of elements. The higher the eigenvalue is, compared to the number of elements, the more inconsistent the pairwise comparisons are. By dividing the inconsistency index by a similar index based on randomly chosen pairwise comparisons, the "inconsistency ratio" is obtained: Saaty suggests that acceptable values for this ratio should not exceed 0.1.' [33, p. 119]

Table 5. List of different defect types observed during AFP deposition.

Observed defects types	*Sketch*	*Example*
1. Loose fibres on surface		
2. Binder accumulation		
3. Foreign material inclusion		
4. Splices		
5. Unintended Gap (>2 mm)		
6. Twisted tape		
7. Tape folding		
8. Tape shearing		
9. Tape overlap		

relationship: influence each other or are dependent on each other). This approach simplifies the nine-step scale in a pairwise comparison to a binary condition describing if two criteria interact (1-state) or are independent (0-state). The sum of the total interactions of a criterion are normalized and used as $w_{i,j}$. The concept is shown in Figure 4.

The CoI approach gives weight to a criteria based on interactions with other the criteria listed, while the experts may consider wider ranging implications when assigning a ranking on a numerical scale. A direct comparison of the approaches highlights the differences in material selection outcome due to the method rather than due to the actual material suitability.

Manufacturing of corner laminate component

In order to make the proposed material selection an industrially viable process, the selected materials were applied to a part that has a higher complexity

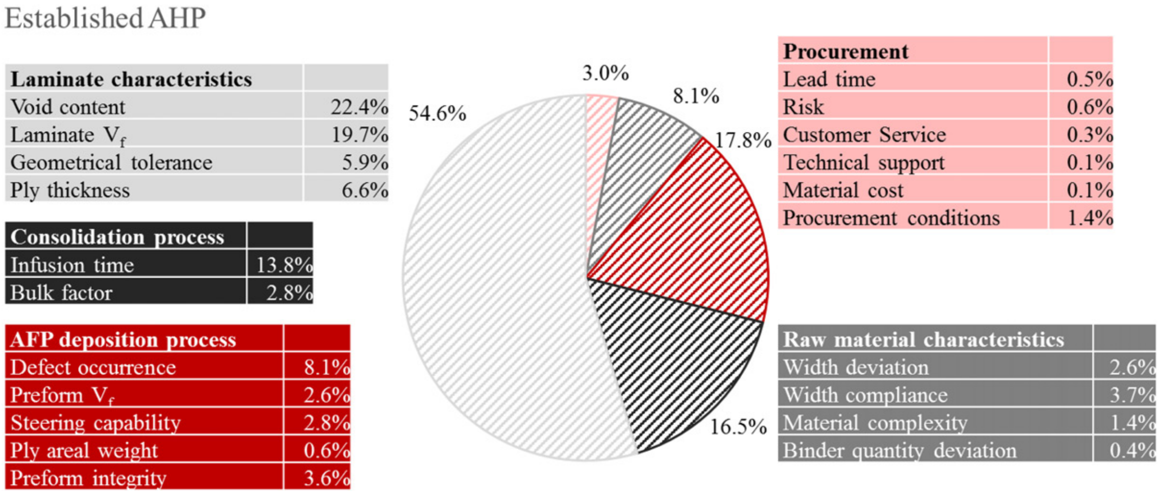


Figure 6. Weightings determined by the established AHP based on the experts' judgement.

than the individual material characterization tests conducted in the sub-criteria assessment stage. The part was a small-scale representative of geometries common in the aerospace industry, which was a symmetrical corner section of 600 mm length and 225 mm flange height, with a 10 mm inner corner radius (see Figure 5). The preforms consist of 26 plies for both materials with a quasi-isotropic stacking sequence. The deposition velocity was limited by the complex machine kinematics and was as low as 5 mm/s in the apex region, and up to 200 mm/s in the flange region. Due to the variable deposition velocity, the laser power was adjusted accordingly. The power law was derived through the process proposed by Di Francesco et al. [30]. The resin used was RTM6 (Hexcel, US), and the preform was infused at supplier recommended set-up and parameters [32,33].

The quality of the corner laminates was assessed against key quality factors: preform and laminate V_f as well as the resulting bulk factor, in addition to void content. A portable ultrasonic C-scanner (Olympus Omniscan MX2 with a 5MHz 64 El Array) was used to check imperfections and voids within the laminates [34]. The part thickness was converted into preform or laminate fiber volume fraction based on nominal areal weight, fiber density and number of plies. To capture any influence of the increase in geometry, two distinct areas of a corner (flanges and the apex) were assessed and compared.

Results and discussion

Material and manufacturing process assessment

A summary of the results of the various quantitative tests of material A to E are shown in Table 4. The bold values are the highest scoring values of the criterion, showing that each material has at least one criterion that scores highest.

The two materials with the lowest areal weight (B and C) showed a very high fault count, as the thin tapes were not as rigid as the other materials and hence prone to twisting or folding. For these lighter materials, a high count of twists and folds (Table 5; defect type 6 and 7) were induced by contact with guiding elements such as the inner ducts in the tape feed tubes (Figure 2(a)) as they shifted due to the robotic motions during the deposition. Tape material manufactured by a slitting process has the lowest variability in width, but at the same time creates edges that might exhibit loose fibers, leading to an increase in fiber residue on the substrate (Table 5; defect type 5 and Figure 2(a)). Tow-based processing results in an areal weight dictated by the fiber count in the precursor tows, while the process of creating a broad good prior to the slitting process allows control over the areal weight and thickness of tapes.

A trained operator inspects each ply of the 3 mm thick $[0/90]_{ns}$ preform during the deposition trials. A defect library was generated, and nine different types of defects were identified (see Table 5).

Material B was the only material not to infuse fully during the vacuum infusion. It was visible from the micrographs that the binder quantity on its surface was lower than all other materials, while the overall binder quantity by weight was close to the quantity in other materials. This indicates that the binder was present within the material rather than on the surface, which could be the reason for its low bulk factor as well as a low permeability. Rimmel et al. have already reported an influence of binder distribution on permeability (in this instance binder content and binder particle size), whereby the latter has greater influence [35]. The material that infused the preform fastest was Material A, which has the distinctive feature of a carbon fiber veil. It was inferred that the veil acted as a highly permeable resin distribution layer between the plies and provides additional flow channels.

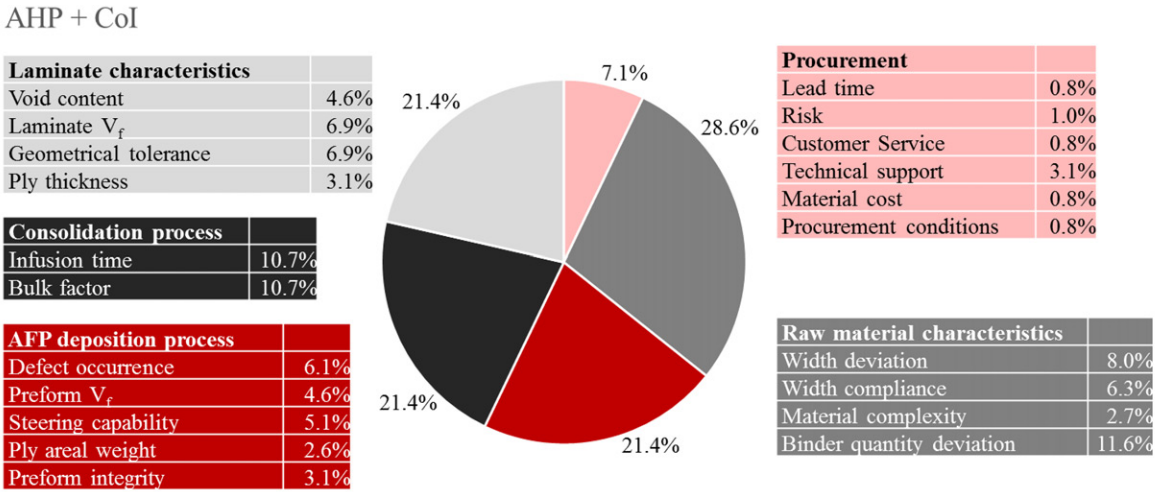


Figure 7. Weightings determined by AHP in conjunction with CoI.

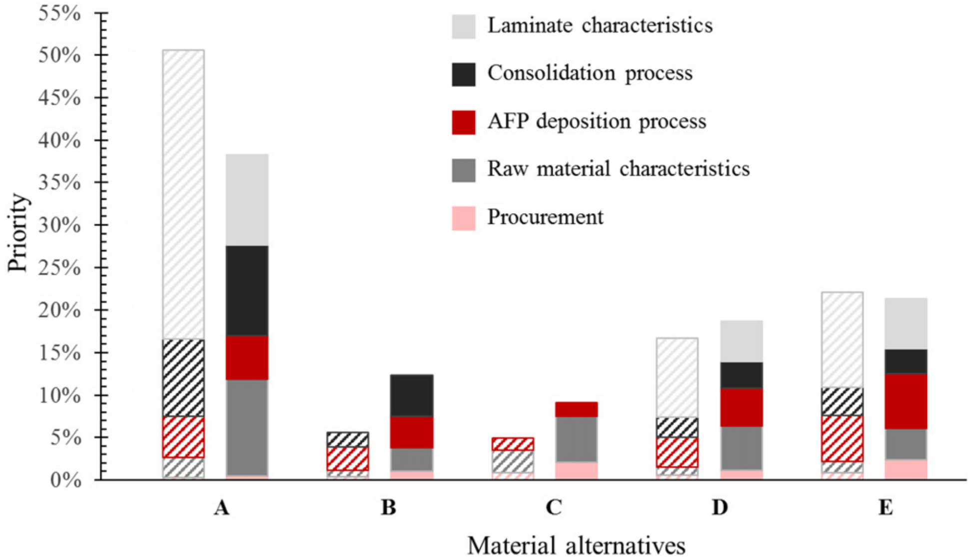


Figure 8. Result of the AHP using different weighting methods for materials A to E; shaded: established AHP, solid: AHP with CoI.

Table 6. Three selected criteria for comparison of two corner panels and their results (error indicates standard deviation).

	Material A	Material D
Sound loss in C-scan	3-6db	3-6db
Average preform V_f		
Corner apex	56.4 ± 1.7%	58.5 ± 1.7%
Corner flange	50.2 ± 0.8%	46.2 ± 2.3%
Difference	6.2%	12.3%
Average laminate V_f		
Corner apex	56.7 ± 0.8%	58.5 ± 0.6%
Corner flange	57.2 ± 0.8%	53.4 ± 2.0%
Difference	0.5%	5.1%
Bulk factor		
Corner apex	1.0	1.0
Corner flange	1.1	1.2
Difference	0.1	0.2

Analytical hierarchy process results

Two different methods were used to determine the weighting of the criteria and compared, as shown in Figures 6 and 7.

As shown in Figure 6, the experts' judgement indicates the highest priority for the laminate characteristics, and therefore a lower importance to the remaining criteria. Experts are more focused on laminate quality of the manufactured part rather than the manufacturing aspects. The part quality is a metric often used in the aerospace industry when buying or selling parts, something all experts are familiar with. Commonly, materials are selected based on their laminate characteristics only as it is assumed any manufacturing challenges are eliminated prior to start production. This, however, may not be the case in this instance of a novel material which is in the product development phase. The AHP + CoI, as shown in Figure 7, shows overall more balanced weighting factors, disregarding external factors such as industrial influence, but only capable of taking the defined criteria into account.

The experts chosen and the way the experts are briefed prior to providing their opinion may have a significant impact on the results. It is important to interrogate experts from a variety of fields relevant to the selection. This is strength and weakness of the established AHP at the same time, the experts are able to tailor the results to the specific case queried and therefore

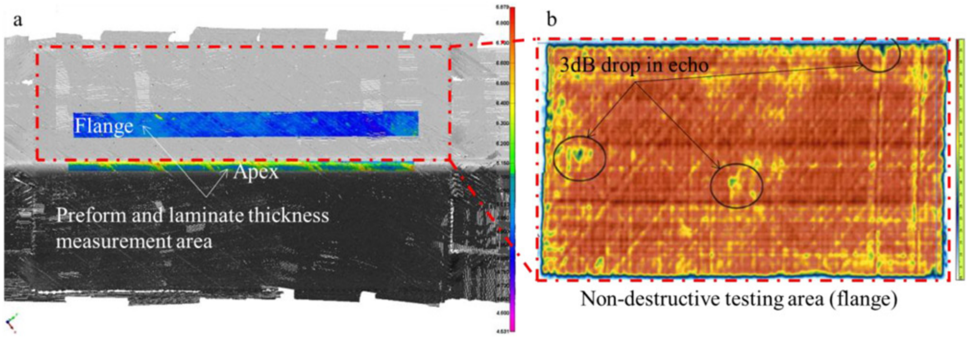


Figure 9. Exemplary measurement results for Material D (a: laser line scan with height color plot; b: ultrasonic scan of flange).

make the result more relevant to the case considered, but is relying on the surrounding factors that are intangible and cannot be captured within the framework. In order to mitigate this, a large pool of people may need to be asked for their opinion. The result of the CoI on the other hand is less dependent on such external factors, but at the same time may neglect relevant industrial influences and the choice of criteria has a more significant impact. The selection of the method used becomes engineering judgement, leading to a decision making paradox.

The results of two different weighting methods for each material are shown in Figure 8, which were obtained by the material assessment results (shown in Table 4) multiplied with their respective weightings (Figures 6 and 7) and summarized using Equation (1).

Material A is ranked equally favorable by both methods. Materials D and E show similar results; a decision between D and E should not be made with confidence due to their close results. Materials B and C are only partially tested, as Material B did not fully infuse and Material C exhibited a high defect count, therefore these materials received the lowest scores. Both methods overall recommend the same material. The manufacturing process has a higher priority within the AHP + CoI method and is well suited to objectively assess a material for manufacturability, while the experts give a higher weight to the laminate and take into account the wider industrial impact. A hybrid method could be explored in the future where main criteria could be assessed by experts to capture the industry needs and the more tangible sub-criteria could be assessed using CoI to provide impartial weighting of the aspects within a criterion. This would keep the effort associated with the opinion gathering at a minimum but enables the capture of a wider industrial focus.

Demonstration of material selection in component manufacture

Material characterization data used in the material selection processes was gathered through layup tests for flat panels. In order to demonstrate the applicability of the material selection processes as well as their suitability for predicting the manufacturing quality of non-flat component, two corner panels were manufactured using Material A (highest priority) and Material D (low priority) and their manufacturing quality was assessed. The quality difference between the corner apex and flanges was of particular interest to check the influence of increased geometrical complexity on the material selection. The key criteria assessed and their results for the two corner laminates are shown in Table 6.

Figure 9(a) shows the top view of the corner panel and the areas used for thickness measurements to calculate the fiber volume fractions before and after resin infusion and cure. Figure 9(b) shows an exemplary result of the C-scan of the flat flange area, where red indicates a very low loss of the back wall echo and therefore signifies a low void content. The green areas show a slightly higher loss of the echo, indicating the potential presence of voids, however, this loss was below the allowable limit of 12 dB for a laminate with less than 5 mm thickness [36]. Both materials show a void content within the acceptable limits.

In the laminates manufactured with Materials A and D, the bulk factor on the apex was lower than that on the flanges, indicating an over-compaction of the material on the apex. The bulk factors of the flat areas were close to the target (1.1), with a lower bulk factor for Material A which indicates higher laminate quality in comparison to Material D. These results are consistent with the flat preform trials.

Material A resulted in a higher average laminate V_f overall, with both apex and flange regions having a V_f above the target of 55%. The difference between apex and flanges was minimal, which is a positive indicator for high consistency and quality. Material D resulted in a low V_f below the minimum target laminate V_f and a higher difference between the apex and the flanges, both indicators for low laminate quality.

Overall, the higher quality laminate was manufactured with Material A, which is consistent with the prediction by the AHP. The detailed comparison between the flat area and the apex area suggests that Material D results in a much more variable laminate induced by geometrical complexity, which has not specifically been captured by the small-scale material characterization tests conducted for the selection criteria. In order to account for this, the material selection process could be expanded by assessing the material behavior under different process conditions, which vary depending on the geometry of the component, i.e. high deposition pressure or low deposition velocity, which would give a higher confidence in the material selection at the penalty of a more extensive test campaign. Despite such a limitation, it was found that the selected criteria were sufficient to suggest the best candidate materials for achieving high manufacturing quality.

Conclusion

A knowledge-based material selection process of dry fiber materials for the use in AFP was proposed on the basis of the AHP.

Most of material selection methods for metals, plastics and sometimes well-characterized composite materials are based on the material properties readily available from literatures or suppliers' catalogues. There are two challenges to apply such methods to the dry fiber AFP process. Firstly, most of the dry fiber tape materials used in the AFP process are relatively new and have not been well-characterized. Secondly, in the dry fiber AFP process, the material behavior of the dry fiber tapes and their respective process ability should be taken into account in the material selection process, which is critical to the final production quality.

This work developed a material selection tool and criteria suitable for the dry fiber materials whose material characteristics and processibility are insufficiently characterized for a conventional decision making process. In order to prevent industrial users having to select suitable materials by spending time and effort with a trial and error approach during the production process, a data driven material selection approach based on lab-scale layup tests was proposed.

Selection criteria were established for commercially available dry fiber materials, the production process and the manufacturing quality by industry experts. Five major criteria (procurement, raw material characteristics, AFP deposition process, consolidation process, laminate characteristics) and 21 sub-criteria defining these criteria were outlined. Five different materials currently available on the market were compared against these criteria, which involved an experimental program. A combination of measurements in manufacturing trials and pairwise comparisons was used to generate the material specific scores for each criterion used in the AHP, resulting in a reusable database.

Using AHP as a knowledge based decision making tool could provide a framework for an extendable database to account for future findings and insights. For instance, upscaling of the process to larger components can require investigating material behavior at high deposition rate, repeatability or robustness of the process. Two different criteria weighting methods were compared; the established AHP which has been used in similar contexts and the CoI method which has been developed to decrease the cost of using the AHP in supplier selection. Both weighting methods recommend the same material but with some difference in scores between materials. Experts' judgement resulted in a higher emphasis on the laminate characteristics than AHP + CoI. The experts are able to tailor their responses to a particular part geometry for the application in the aerospace industry resulting in a focus on laminate quality. CoI exclusively takes into account the selected criteria, resulting in a focus on the manufacturing aspects. The choice of method may alter the result in other cases, a hybrid method to capture both aspects was proposed.

The selected materials were used to manufacture a representative part geometry, and the quality aspects influenced by the increased geometrical complexity were examined. It was found that the results of a material selection based on flat samples recommend the same material as a direct comparison of a more complex part. A more extensive material test campaign could increase certainty for selecting a suitable material for AFP production of highly complex geometries at the penalty of increased cost to gather data.

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Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Laura Veldenz http://orcid.org/0000-0002-5426-4656

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